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Electroweak decay of quark matter within combustion flames at compact objects

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Abstract

Just after the phase transition from hadronic to quark matter in neutron stars, weak interactions drive quark matter to thermal and chemical equilibrium. We calculate the reaction rate and the neutrino emissivity for all the relevant weak interaction processes in hot and dense quark matter and solve the Boltzmann equation in order to describe the time evolution of the system. We find that the neutrino emissivity per baryon is very large, leading to an energy release per baryon of 10−60 MeV in the form of neutrinos.

Keywords: neutron stars, quark matter, combustion

1. Introduction

In compact stars, the formation of quark matter begins with the nucleation of small deconfined drops inside the stellar core when the density of hadronic matter goes beyond a critical density (see [1] and references therein). The formation of such drops occurs in two steps. First, hadrons composing nuclear matter deconfine in a strong interaction time scale of $\sim 10^{-23}$ seconds to quark matter, leaving a quark gas which is not in equilibrium under weak interactions. Later, weak interactions chemically equilibrate the system in a time scale of $\sim 10^{-9}$ sec. As a result of these decays, quark matter in chemical equilibrium is produced, temperature is significantly increased, and a great amount of neutrinos is produced. The energy released in such conversion can ignite hadronic matter in the neighborhood of the drop, and as a consequence it may grow and convert to quark matter the core of the star and even the whole star if quark matter is absolutely stable. During the conversion, a combustion front (flame) separating the unburnt hadronic matter from the burnt quark matter travels outwards along the star [2]. In this work we are interested in how quark matter within the flame approaches to equilibrium just after the deconfinement transition.

In a cold deleptonized neutron star (NS), the relevant processes just after deconfinemet of hadronic matter are $d \rightarrow u + e^- + \bar{\nu}_e$, $s \rightarrow u + e^- + \bar{\nu}_e$, $u + e^- \rightarrow d + \nu_e$, $u + e^- \rightarrow s + \nu_e$ and $u + d \leftrightarrow u + s$. In a hot neutrino-rich protoneutron star (PNS) the processes are $u + e^- \leftrightarrow d + \nu_e$, $u + e^- \leftrightarrow s + \nu_e$ and $u + d \leftrightarrow u + s$ [3]. In Sec. 2 we give the rates and the neutrino emissivities for all the relevant processes. In Sec. 3 we solve the Boltzmann equation and describe the time evolution of the system as it approaches chemical equilibrium.

2. Reaction rates and neutrino emissivities

The reaction rates and neutrino emissivities have been calculated in previous works for two different approximate cases [3]: (1) cold deleptonized NS matter, where quarks and electrons are degenerate, and (2) hot neutrino rich PNS matter, where quarks, electrons and neutrinos can be treated as degenerate. In this work we generalize these results and obtain the reaction rates and neutrino emissivities assuming degenerate quarks and electrons, but without making any assumption about the degeneracy state of neutrinos. Due to space limitations we shall show only the results; the derivations will be presented in detail elsewhere [5].

The reaction rate for the decay process $d \rightarrow u + e^- + \bar{\nu}_e$

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is

$$\Gamma_1 = c_1 \int_0^{\infty} \frac{(\mu_u + \mu_e - \mu_d + E_{\bar{\nu}_e})^2 + \pi^2 T^2}{2[e^{(\mu_u+\mu_e-\mu_d+E_{\bar{\nu}_e})/T} + 1]} \times \frac{I(\mu_u, \mu_e, \mu_d, E_{\bar{\nu}_e})}{e^{(\mu_{\bar{\nu}_e}-E_{\bar{\nu}_e})/T} + 1} dE_{\bar{\nu}_e}, \quad (1)$$

where $c_1 = 3G_F^2 \cos^2\theta_C/(2\pi^5)$ and $I(\mu_u, \mu_e, \mu_d, E_{\bar{\nu}_e})$ is the angular integral I_{12} given in Ref. [4]. The rate Γ_2 for the process $s \to u + e^- + \bar{\nu}_e$ can be obtained replacing μ_d by μ_s and $\cos^2\theta_C$ by $\sin^2\theta_C$ in the latter expression.

For the process $u + e^- \leftrightarrow d + \nu_e$ we find

$$\Gamma_3^{dir} = c_1 \int_0^{\infty} \frac{(\mu_u + \mu_e - \mu_d - E_{\nu_e})^2 + \pi^2 T^2}{2[e^{(\mu_u+\mu_e-\mu_d-E_{\nu_e})/T} + 1]} \times \frac{J(\mu_u, \mu_e, \mu_d, E_{\nu_e})}{e^{(\mu_{\nu_e}-E_{\nu_e})/T} + 1} dE_{\nu_e} \quad (2)$$

for the direct process (electron capture by u quarks) and $\Gamma_3^{rev} = e^{-(\mu_u+\mu_e-\mu_d-\mu_{\nu e})/T}\Gamma_3^{dir}$ for the reverse process (neutrino absorption by d quarks).

The rate Γ_4^{dir} for $u + e^- \to s + \nu_e$ can be obtained replacing μ_d by μ_s and $\cos^2\theta_C$ by $\sin^2\theta_C$ in the expression for Γ_3^{dir}. For the reverse process $s + \nu_e \to u + e^-$ we have $\Gamma_4^{rev} = e^{-(\mu_u+\mu_e-\mu_s-\mu_{\nu e})/T}\Gamma_4^{dir}$.

Finally, for $u_1 + d \to u_2 + s$ we have

$$\Gamma_5^{dir} = c_2 \int_{m_s}^{\infty} \frac{(\mu_d - E_s)^2 + \pi^2 T^2}{2[e^{(\mu_d-E_s)/T} + 1]} \times \frac{J(\mu_u, \mu_d, \mu_u, E_s)}{e^{(\mu_s-E_s)/T} + 1} dE_s, \quad (3)$$

where $J(\mu_u, \mu_d, \mu_u, E_s)$ is the angular integral J_{12} given in Ref. [4], and $c_2 = 9G_F^2 \sin^2\theta_C \cos^2\theta_C/(2\pi^5)$. The rate for the reverse process $u + s \to u + d$ is given by $\Gamma_5^{rev} = e^{-(\mu_d-\mu_s)/T}\Gamma_5^{dir}$.

The neutrino emissivity rate per baryon is given below for all the relevant processes. For $d \to u + e^- + \bar{\nu}_e$ we have

$$\varepsilon_1 = c_1 \int_{-\infty}^{\mu_{\bar{\nu}_e}} \frac{(\mu_u + \mu_e - \mu_d + E_{\bar{\nu}_e})^2 + \pi^2 T^2}{2[e^{(\mu_u+\mu_e-\mu_d+E_{\bar{\nu}_e})/T} + 1]} \times \frac{I(\mu_u, \mu_e, \mu_d, E_{\bar{\nu}_e})}{e^{(\mu_{\bar{\nu}_e}-E_{\bar{\nu}_e})/T} + 1} E_{\bar{\nu}_e} dE_{\bar{\nu}_e}. \quad (4)$$

The emissivity ε_2 for $s \to u + e^- + \bar{\nu}_e$ can be obtained replacing μ_d by μ_s and $\cos\theta_C$ by $\sin\theta_C$ in the previous expression. For $u + e^- \to d + \nu_e$ we find

$$\varepsilon_3 = c_1 \int_{-\infty}^{\mu_{\nu_e}} \frac{(\mu_u + \mu_e - \mu_d - E_{\nu_e})^2 + \pi^2 T^2}{2[e^{(\mu_u+\mu_e-\mu_d-E_{\nu_e})/T} + 1]} \times \frac{J(\mu_u, \mu_e, \mu_d, E_{\nu_e})}{e^{(\mu_{\nu_e}-E_{\nu_e})/T} + 1} E_{\nu_e} dE_{\nu_e}. \quad (5)$$

Similarly, the emissivity ε_4 for $u + e^- \to s + \nu_e$ is obtained replacing μ_d by μ_s and $\cos\theta_C$ by $\sin\theta_C$ in the previous formula.

The total neutrino emissivity in a NS is $\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4$. For a PNSs we have $\varepsilon = \varepsilon_3(1 - e^{-\xi_d}) + \varepsilon_4(1 - e^{-\xi_s})$ where $\xi_d = (\mu_u + \mu_e - \mu_d - \mu_{\nu_e})/T$ and $\xi_s = (\mu_u + \mu_e - \mu_s - \mu_{\nu_e})/T$.

3. Results and discussion

Considering the processes given at the end of Sec. 1 for a cold NS, we find

$$\frac{dY_u}{dt} = \frac{1}{n_B}\left[\Gamma_1 + \Gamma_2 - \Gamma_3^{dir} - \Gamma_4^{dir}\right], \quad (6)$$

$$\frac{dY_d}{dt} = \frac{1}{n_B}\left[-\Gamma_1 + \Gamma_3^{dir} - \Gamma_5^{dir} + \Gamma_5^{rev}\right], \quad (7)$$

where Y_i is the abundance of the i-species (the number of particles of the i-species per baryon). The abundances of s quarks and electrons are given by baryon number conservation $Y_s = 3 - Y_u - Y_d$ and charge neutrality $Y_e = Y_u - 1$. Neutrinos leave the system freely.

The temperature evolution can be obtained from the first law of thermodynamics,

$$\alpha \frac{dT}{dt} = \sum_i \left\{ n_B T \left(\frac{\partial s}{\partial \mu_i}\right)_T \left(\frac{\partial n_i}{\partial \mu_i}\right)_T^{-1} - \mu_i \right\} \frac{dY_i}{dt}, \quad (8)$$

with

$$\alpha \equiv C_v - T\left(\frac{\partial s}{\partial T}\right)_\mu + T \sum_i \left(\frac{\partial s}{\partial \mu_i}\right)_T \left(\frac{dn_i}{dT}\right)_\mu \left(\frac{\partial n_i}{\partial \mu_i}\right)_T^{-1}, \quad (9)$$

where $C_v = 9.86T \sum_i \frac{Y_i}{p_F(i)}$ is the specific heat per baryon of a mixture of free relativistic fermions. Integrating the above equations numerically, we can obtain the time evolution of the particle abundances and the temperature as the system approaches equilibrium. As initial conditions, we consider the state of just deconfined quark matter calculated in Ref. [6].

Our calculations show that after the deconfinement phase transition, the subsequent conversion to quark matter in equilibrium under weak interactions significantly increases the temperature T and the strange quark abundance Y_s in a timescale of $\sim 10^{-9}$ s. The abundances of the other particles Y_u, Y_d, Y_e decrease. Due to space limitations we shall show these results elsewhere [5]. Since the calculations provide the time evolution of the temperature T and the chemical potentials of all particle species, we are able to determine the relevance of the different weak interaction processes as matter approaches equilibrium. This is shown in Fig. 1 for the conversion in a cold deleptonized NS. In that figure we see that the nonleptonic process $u + d \to u + s$ dominates the rate until matter reaches chemical equilibrium.

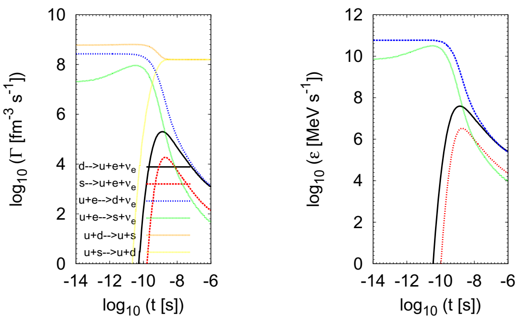

Figure 1: The reaction rate per unit volume and the neutrino emissivity per baryon as a function of time in a NS for all the relevant processes. We consider $\alpha_c = 0$, $B = 80$ MeV fm^{-3}, $m_s = 200 MeV$ and $T_i = 0$ MeV.

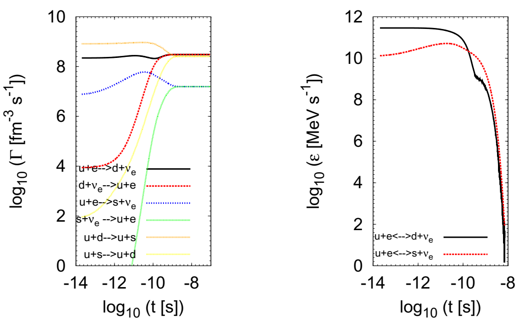

Figure 2: Same as the previous figure but for a PNS; we use $T_i = 20$ MeV.

We also observe that the contribution of the decay of s and d quarks to the total rate is always negligible. After 10^{-9} s, chemical equilibrium is maintained essentially by the two nonleptonic processes $u + d \leftrightarrow u + s$. The electron capture reactions have a smaller contribution to the rate, but they are the most important processes that emit neutrinos (see right panel of Fig. 1).

For a transition to quark matter taking place in a PNS, the lepton number $Y_L = Y_e + Y_\nu$ is constant because neutrinos are trapped. Considering the processes given at the end of Sec. 1 for a PNS the time evolution of Y_u and Y_d is given by:

$$\frac{dY_u}{dt} = \frac{1}{n_B}\left[\Gamma_3^{rev} - \Gamma_3^{dir} + \Gamma_4^{rev} - \Gamma_4^{dir}\right], \tag{10}$$

$$\frac{dY_d}{dt} = \frac{1}{n_B}\left[\Gamma_3^{dir} - \Gamma_3^{rev} - \Gamma_5^{dir} + \Gamma_5^{rev}\right]. \tag{11}$$

The other equations are the same as for the NS case. In Fig. 2 we see that in a hot PNS, the nonleptonic process $u+d \to u+s$ is dominant most of the time, like in a cold deleptonized NS. However, near chemical equilibrium, the process $u + e^- \leftrightarrow d + \nu_e$ becomes relevant and at the end it has the largest rate. The net neutrino energy loss per baryon is shown in the right panel of Fig. 2 for the processes $u + e^- \leftrightarrow d + \nu_e$ and $u + s \leftrightarrow d + \nu_e$. The emissivity is high during $\sim 10^{-10}$ s and is followed by a steep decline to a value five orders of magnitude smaller in a timescale of $\sim 10^{-8}$ s. The maximum value of the emissivity per baryon is between 10^{10} MeV/s and 10^{12} MeV/s as for the NS. Initially, most neutrinos are emitted as a consequence of the $u+e^- \leftrightarrow d+\nu_e$ process, but around $t \approx 10^{-10}$ s the emissivity of this process falls significantly. On the other hand, the emissivity of the process $u+e^- \leftrightarrow s+\nu_e$ gains relevance as the abundance of s quarks becomes large.

We have integrated in time the total neutrino emissivity and obtained the total energy per baryon released by quark matter in the form of neutrinos. For cold neutron stars we find that the energy release is $E_{\nu_e} = 30 - 60$ MeV per baryon and for protoneutron stars it is $E_{\nu_e} = 10 - 55$ MeV. This is a very large value that may lead to dramatic astrophysical consequences. As a rough estimate we can consider a typical neutron star with 10^{58} baryons, which means that a neutron star can emit an energy of around $\sim 10^{53}$ erg. This energy is of the same order of the gravitational binding energy of the compact object i.e. the conversion process has enough energy to disrupt the star. In the case of a protoneutron star these neutrinos can be absorbed by the matter just behind the shock wave that travels along the external layers of the progenitor star, and help to a successful core collapse supernova explosion. Notice also that the liberated energy is of the order of the energy of a gamma ray burst (GRB), indicating that models of GRBs involving the hadron to quark conversion in a neutron star deserve further study.

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